

Prospects for Nuclear Electric Propulsion Using Closed-Cycle Magnetohydrodynamic Energy Conversion*

Ron Litchford

Leo Bitteker

Jonathan Jones

Tara Poston

**National Aeronautics and Space Administration
George C. Marshall Space Flight Center**

***Originally presented at 39th AIAA Aerospace Sciences Meeting, Reno NV (AIAA 2001-0961)**



Space Transportation Directorate



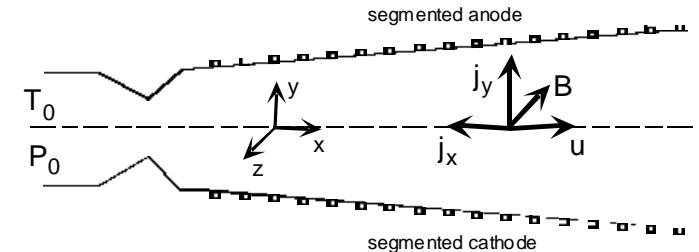
- Truly meaningful deep space exploration requires high energy density concepts
 - beamed energy/momentum and other off-board resources
 - nuclear fission & fusion
 - matter-antimatter annihilation (highest known energy density)
- Nuclear Fission Power Plant with MMW EP Appears to be Best Near-Term Prospect
 - highest overall TRL
 - competitive energy density
- Nuclear Turbogenerator Space Power Plants are Next Evolutionary Step
 - low risk development but limited effectiveness ($a \sim 5 - 10 \text{ kg/kW}_e$)
 - operates at low heat rejection temperatures ($a_{\text{rad}} \propto 1/T^4$)
 - peak cycle temperature constrained by turbine blade solid temperature limit
 - no clear development path to obtain $a < 1 \text{ kg/kW}_e$

... How can NEP break through 1 kg/kW_e barrier?

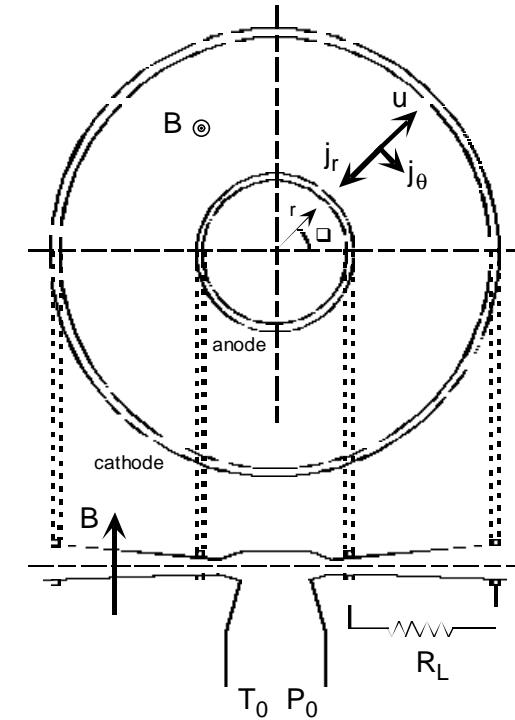


MHD Energy Conversion ...

- Space Nuclear MHD concepts (R. J. Rosa – 1960s)
- Ability to extract energy at arbitrarily high temperature
 - solid core reactor to 2500 K (NERVA)
 - fixed particle bed reactor to 3000 K
 - gas core reactor to 8000 – 10,000 K
- Linear or disk generator configurations are suitable
 - nonequilibrium Hall disk highly attractive
 - heat transfer rate determines thermal limits
- Revive & amplify concept for NEP
- Preliminary system analysis
 - thermodynamic cycle analysis
 - aggregate specific mass analysis
 - assess technology development status
 - potential payoff vs. development risk



Linear MHD Generator

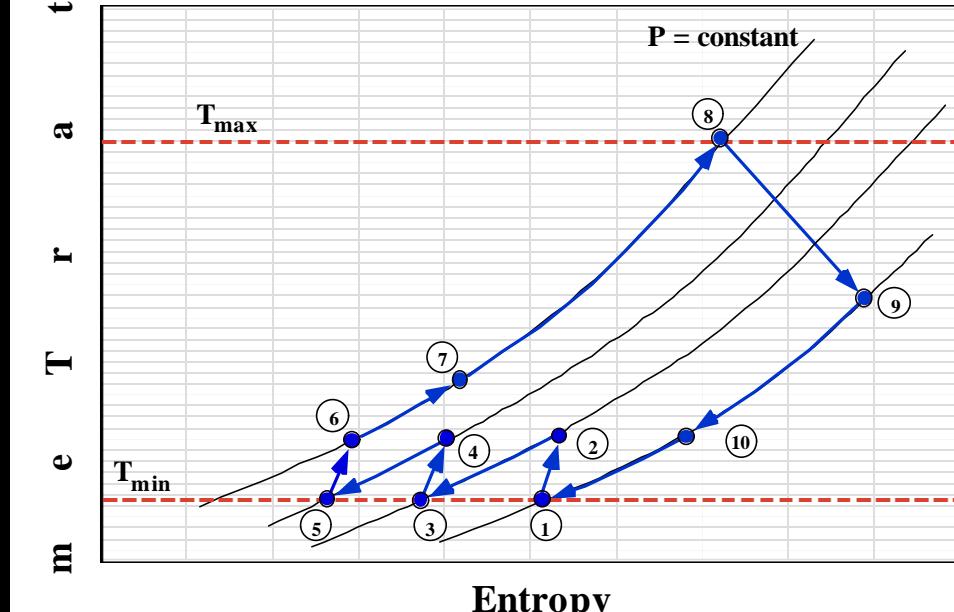
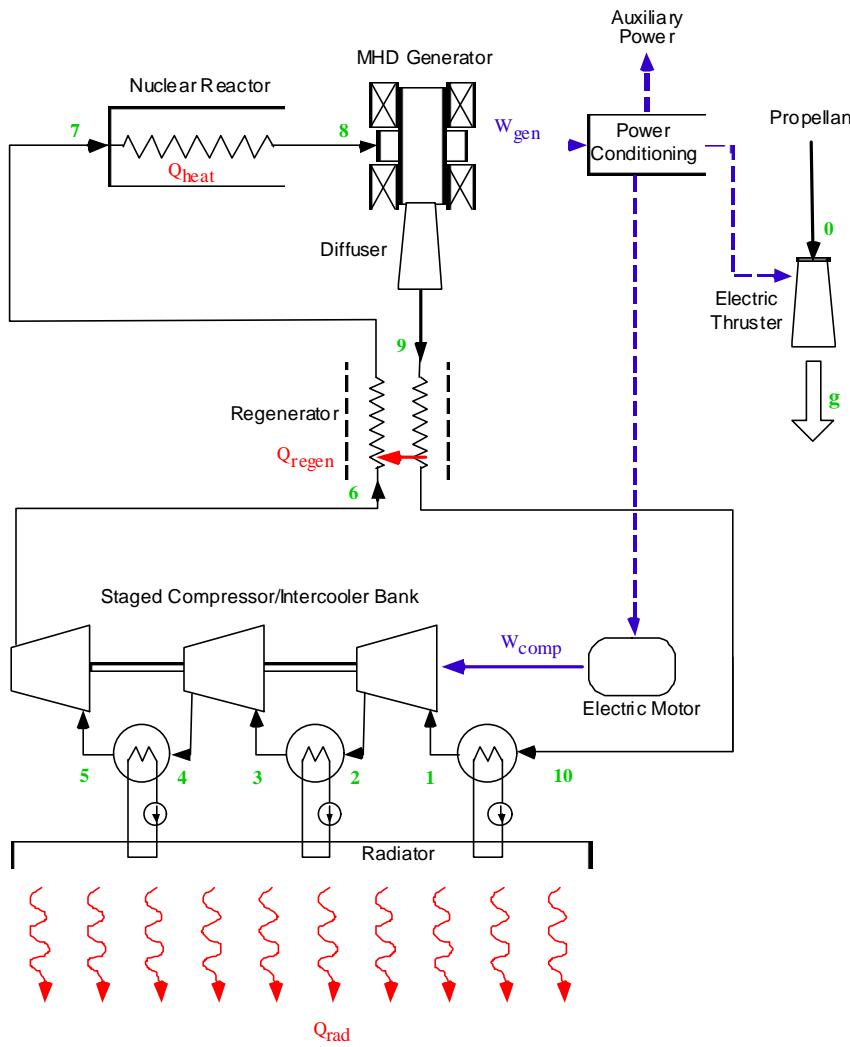


Hall Disk MHD Generator



Nuclear Brayton MHD Space Power for EP

Marshall Space Flight Center



Brayton Cycle vs. Rankine Cycle

- Brayton slightly inferior in performance
- Avoids highly corrosive condensing vapors (i.e., can utilize inert gas working fluid)
- Compatible with solid-core reactors (i.e., leverage NERVA technology base)



Thermodynamic Cycle Analysis

Marshall Space Flight Center

Assumptions:

- Thermally/Calorically Perfect Gas
- Fixed Operating Temperatures

$$T_{\max} = T_{\text{reactor}}$$

$$T_{\min} = T_{\text{radiator}}$$

Energy Convertor Parameters:

- Enthalpy Extraction Ratio

$$h_N = \frac{\Delta h_{gen}}{h_{ent}}$$

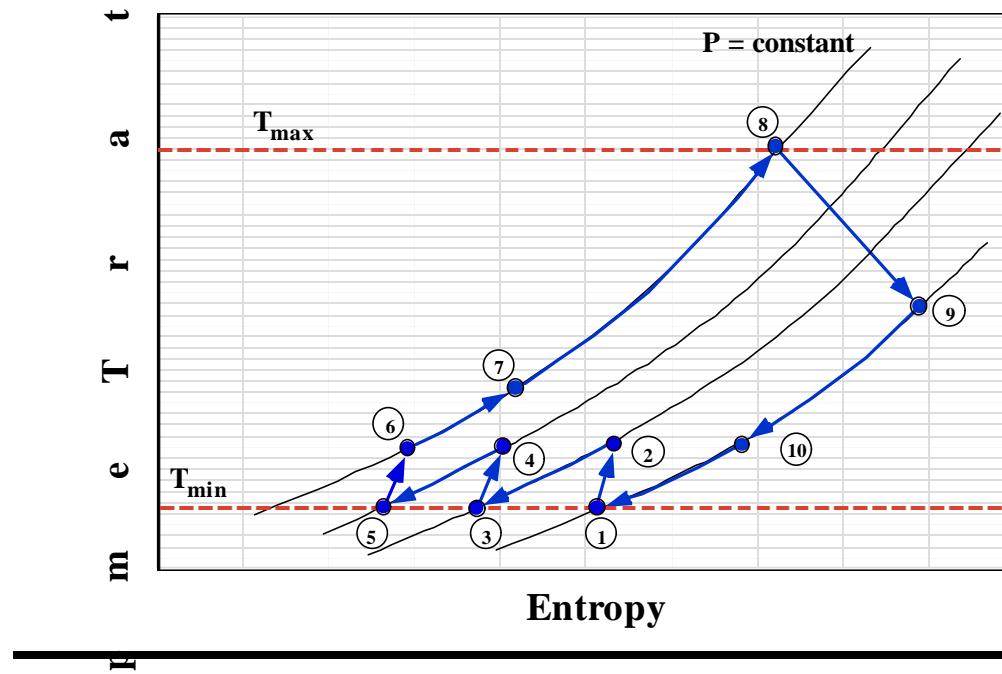
- Isentropic Efficiency

$$h_{s,g} = \frac{\Delta h_{gen}}{\Delta h_{gen,s}}$$

- Stagnation Pressure Ratio

$$p_{\text{gen}} = p_{\text{out}} / p_{\text{in}}$$

$$h_N = h_{s,g} \left[1 - p_g^{\frac{g-1}{g}} \right]$$



Thermal Efficiency:

$$h_{th} = \frac{W_{\text{thruster}}}{Q_{\text{reactor}}} = \frac{W_{\text{gen}} - W_{\text{comp}}}{Q_{\text{reactor}}}$$

$$h_{th} = \frac{h_{s,g} \left[1 - p_g^{\frac{g-1}{g}} \right] T_{\max} - \frac{N_c}{h_{s,c}} \left[p_g^{\frac{g-1}{N_c g}} - 1 \right] T_{\min}}{\left[1 - e_{\text{regen}} \left\{ 1 - h_{s,g} \left[1 - p_g^{\frac{g-1}{g}} \right] \right\} T_{\max} - (1 - e_{\text{regen}}) \left\{ 1 + \frac{1}{h_{s,c}} \left[p_g^{\frac{g-1}{N_c g}} - 1 \right] \right\} T_{\min} \right]}$$



Thermal Efficiency not Central Consideration for Space Systems ...

Must examine overall mass relative to performance ® specific mass

Power Plant Aggregate :

$$\mathbf{a}_{plant} = \frac{\mathbf{a}\hat{q}|_{reactor} + \mathbf{a}\hat{w}|_{gen} + \mathbf{a}\hat{w}|_{comp} + \mathbf{a}\hat{q}|_{regen} + \mathbf{a}\hat{q}|_{rad}}{\hat{w}_{gen} - \hat{w}_{comp}}$$

Propulsion System Aggregate :

$$\mathbf{a}_{system} = \mathbf{a}_{plant} + \mathbf{a}_{thrust}$$



Fission Reactor Specific Mass

Marshall Space Flight Center

Solid Core & Fixed Particle Bed Reactor Technology ...

- 2500 – 3000 K peak operating temperature range
 - Solid core NERVA technology base
 - 2500 K design operating temperature
 - moderate risk development path to 3000 K (carbide elements)
 - Westinghouse (Holman, 1987) design extrapolation from NERVA technology
 - 1350 MW_{th}
 - 1785 kg reactor mass
- $a_{reactor} = 5 \text{ kg/MW}_{\text{th}}$

Reactor Specific Mass Estimate ...

- Reactor mass independent of power level
- Assume $m_{reactor} = 3000 \text{ kg}$ (includes margin for shielding)

$$a_{reactor} = \frac{m_{reactor}}{Q_{reactor}} = \frac{3000 \text{ kg}}{Q_{reactor}}$$



MHD Generator Mass Characteristics

Marshall Space Flight Center

High B Desirable for Optimal MHD Device Performance ...

- Large energy density ($P_{gen} \mu su^2 B^2$)
 - Large Hall parameter ($b \mu B/p$)
 - High isentropic efficiency ($b > 10$)

Weight of Generator Dominated by Weight of Magnet ...

$$\mathbf{a}_{gen} \approx \mathbf{a}_{magnet} = \mathbf{a}_{struc} + \mathbf{a}_{coil}$$

Superconductor Magnets Needed for Space Applications ...

- High field resistive magnets have severe heat dissipation problem
 - High power consumption / High waste heat rejection
 - Cooling limited for high fields (e.g., $\sim 10 \text{ W/mm}^3$)



Magnetic Confinement Structure

Marshall Space Flight Center

Basic Challenge of Large Volume High Field Magnet Design ...

- Magnetic field falls off with distance from coil as $1/r^2$
 - Current must be high to fill large working volume
 - Large currents lead to extreme Lorentz forces on the coil

$$\mathbf{B} = \frac{\mu_0}{4\pi} \frac{i d\mathbf{l} \times \mathbf{a}_r}{r^2}$$

$$d\mathbf{F} = i d\mathbf{l} \times \mathbf{B}$$

P *large confinement structure*

Stored Magnetic Field Energy ...

$$W_m = \iiint_V \underbrace{\frac{B^2}{2\mu_0}}_{\text{magnetic energy density}} dV \cong \frac{B^2}{2\mu_0} V$$

$$\frac{W_m}{V} \approx 4 \times 10^7 \text{ J/m}^3 \quad @ \quad 10 \text{ Tesla}$$



Virial Theorem ...

(Ideal hoop tension to contain stored energy)

$$m_{\text{struc}} \geq \frac{\mathbf{r}}{s_t} W_m$$

P

$$m_{\text{struc}} \cong \frac{\mathbf{r}}{s_t} \frac{B^2}{2m_0} V$$

mass-to-energy ratio

Virial Theorem Requirements

Material	$W_m/m = s_t/\mathbf{r}$ (kJ/kg)
fiber-reinforced composites	10 – 50
stainless steel (304LN)	44
aluminum (2219T851)	107
titanium	309
beryllium-copper	580



Confinement Structure Specific Mass

Marshall Space Flight Center

Combine Field Energy Definition with Virial Theorem ...

$$a_{struc} = \frac{m_{struc}}{W_{gen}} = \frac{r}{s_t} \frac{B^2}{2m_0} \frac{V}{W_{gen}}$$

Introduce Generator Power Density Parameter ($P_{gen} = W_{gen}/V$) ...

$$a_{struc} = \frac{r}{s_t} \frac{B^2 / 2m_0}{P_{gen}}$$



Helmholtz Coil Winding: Disk Generator

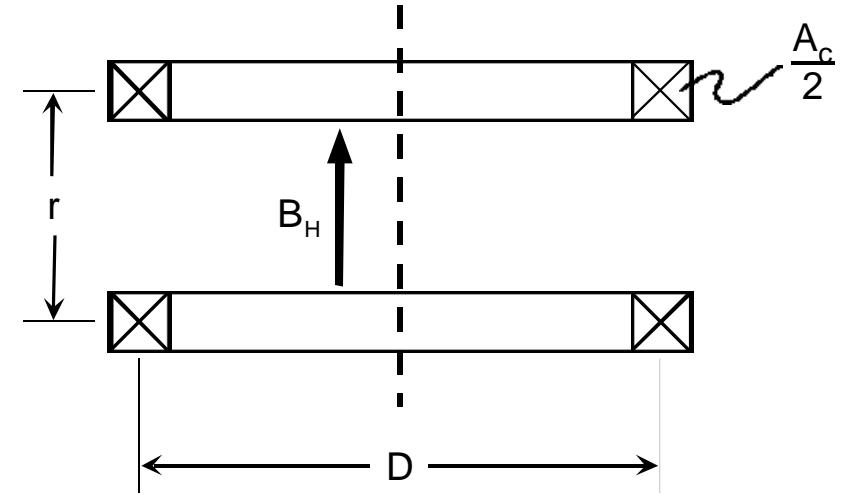
Marshall Space Flight Center

Dual Coil Cross-Section ...

- Assume disk generator with $r/h \gg 10$ ($D/h \gg 20$)

$$V_{gen} = \frac{W_{gen}}{P_{gen}} = \frac{\mathbf{p}}{4} D^2 h = \frac{\mathbf{p}}{80} D^3$$

$$\mathbf{p} \quad D = \left(\frac{80}{\mathbf{p}} \frac{W_{gen}}{P_{gen}} \right)^{1/3}$$



- Cross sectional area of winding

$$A_c = \frac{\sqrt{2} B_H}{\mathbf{m}_0 j_c} \left(\frac{80}{\mathbf{p}} \frac{W_{gen}}{P_{gen}} \right)^{1/3}$$

$$B_H = \frac{B_0}{\sqrt{2}} = \frac{\mathbf{m}_0 i}{2\sqrt{2}r} = \frac{\mathbf{m}_0 j_c A_c}{\sqrt{2}D}$$

Coil Specific Mass ...

$$a_{coil} = \frac{m_c}{W_{gen}} = \frac{\sqrt{2} \mathbf{p} r_c B_H D^2}{\mathbf{m}_0 j_c W_{gen}}$$



Specific Mass of Standardized Components

Marshall Space Flight Center

Parameter estimates based on broad body of technical experience

Turbo-Compressor Group ...

$$\mathbf{a}_{comp} = \frac{m_{comp}}{W_{comp}} = 2 \times 10^{-5} \text{ kg/W}$$

Regenerator ...

$$Q_{regen} = U_{regen} \Delta T_{LMD} A_{regen} \quad \mathbf{b}_{regen} = \frac{m_{regen}}{A_{regen}} = 1 \text{ kg/m}^2$$

$$\mathbf{a}_{regen} = \frac{m_{regen}}{Q_{regen}} = \frac{\mathbf{b}_{regen}}{U_{regen} \Delta T_{LMD}}$$

Radiator ...

$$Q_{rad} = \mathbf{es} A_{rad} T_{\min}^4 \quad \mathbf{b}_{rad} = \frac{m_{rad}}{A_{rad}} \approx 2 - 0.2 \text{ kg/m}^2$$

$$\mathbf{a}_{rad} = \frac{m_{rad}}{Q_{rad}} = \frac{\mathbf{b}_{rad}}{\mathbf{es} T_{\min}^4}$$



High-Power Electric Thruster Specific Mass

Marshall Space Flight Center

High Power (MW-class) Electric Thrusters ...

- Yet to be demonstrated in the laboratory
- Many EP specialists tend to be skeptical
- Must be efficient, compact, and reliable at high-power levels

Object of Current Research Efforts

Thruster Specific Mass ...

$$a_{thrust} = \frac{m_{thrust}}{W_{thrust}} = \frac{m_{thrust}}{W_{gen} - W_{comp}}$$

Electric Thruster Characteristics

Device	I_{sp} (sec)	h	a (kg/kW _e)
Ion (Kr)	≥ 5000	0.8	1.0
MPD (Li)	4000 – 8000	0.5	0.5
MPD (H ₂)	≥ 8000	0.5	0.5
VASIMR (H ₂)	3000 – 30,000	0.5	0.2 – 1.0

Approximated Parameter Range



Power Plant Thermal Efficiency

Marshall Space Flight Center

MHD Brayton Power Plant

Helium Working Fluid

$T_{\max} = 2500 \text{ K}$

$e_{\text{regen}} = 0.9$

$h_{s,g} = 0.70$

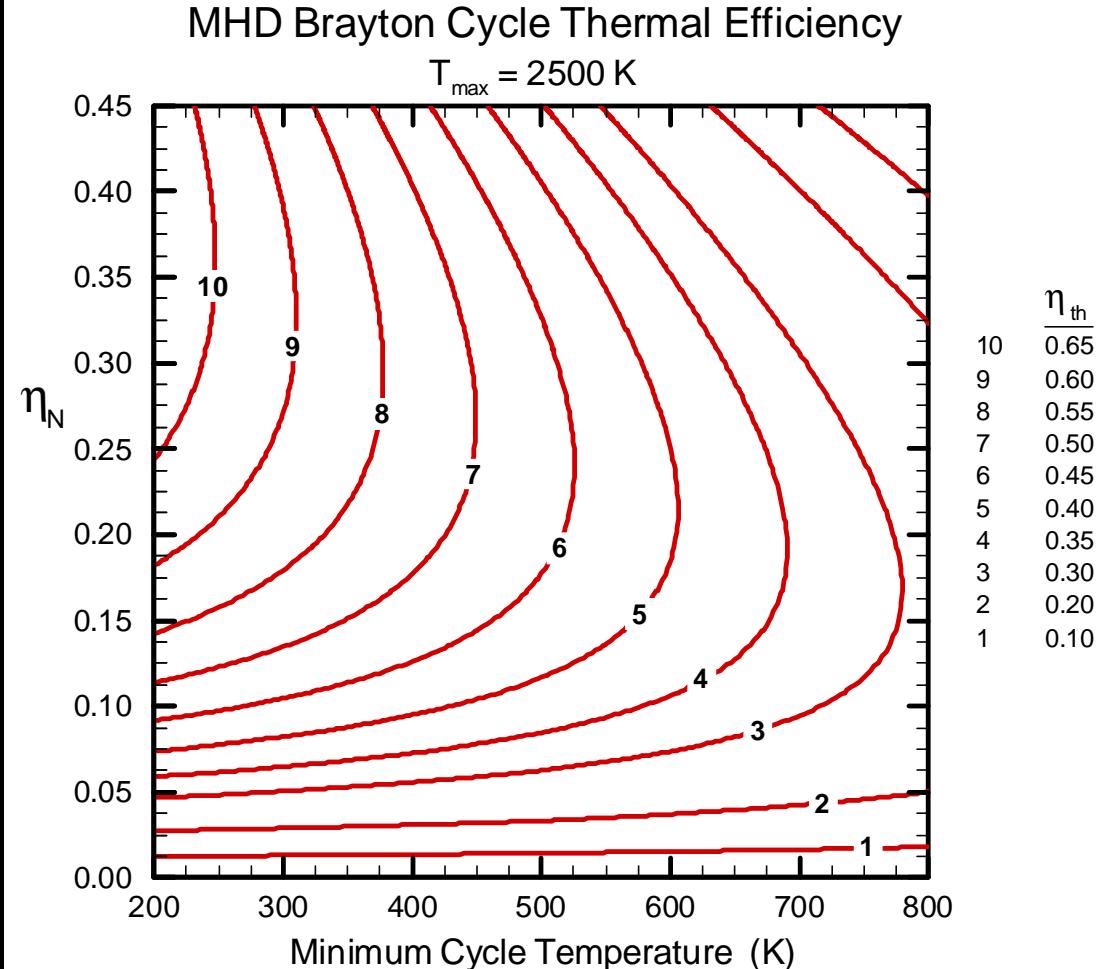
$h_{s,c} = 0.87$

$p_g = 2 - 12$

$T_{\min} = 200 \text{ K} - 800 \text{ K}$

$$h_N = h_{s,g} \left[1 - p_g^{\frac{-g-1}{g}} \right]$$

$$h_{th} = \frac{W_{\text{thruster}}}{Q_{\text{reactor}}} = \frac{W_{\text{gen}} - W_{\text{comp}}}{Q_{\text{reactor}}}$$





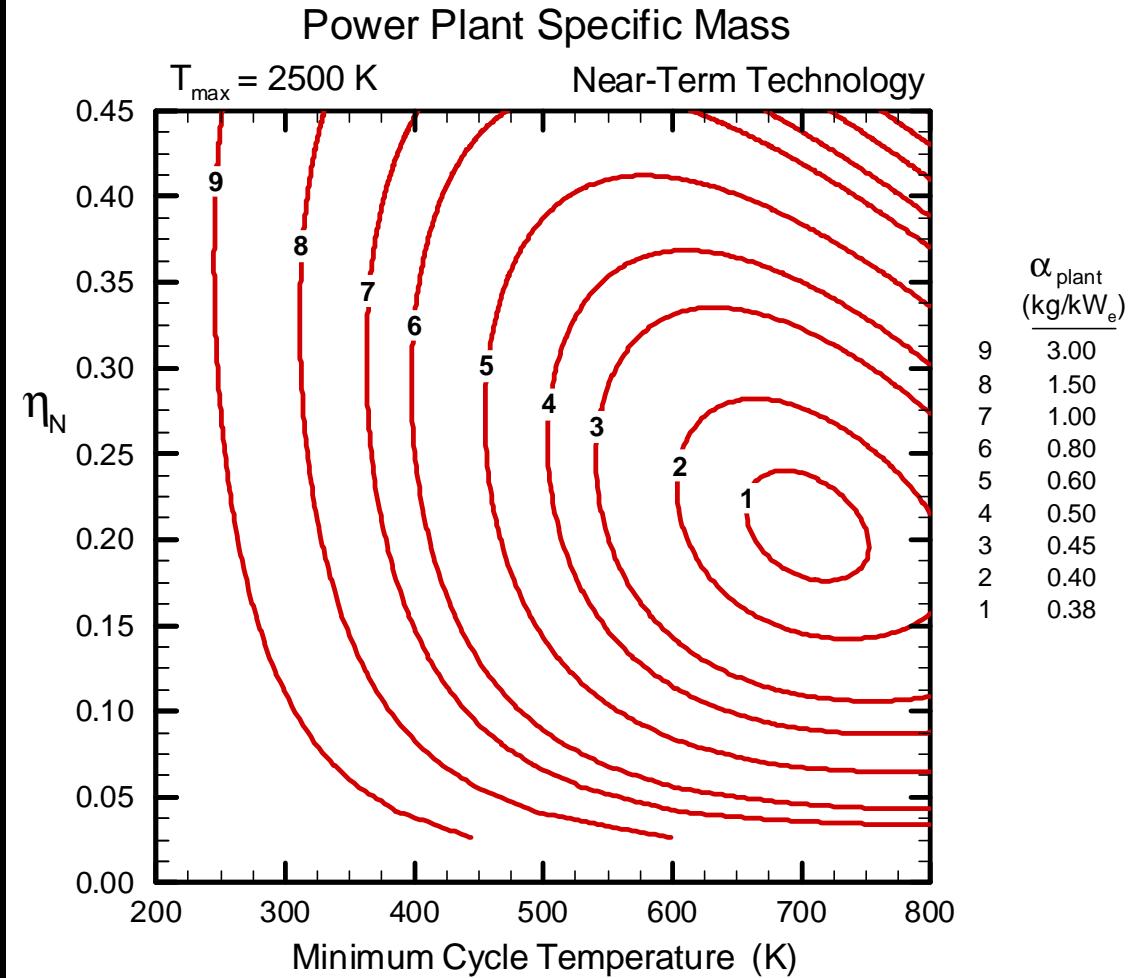
Power Plant Specific Mass: Near-Term Technology

Marshall Space Flight Center

Disk MHD Brayton Power Plant

Subsystem Technology Assumptions

Parameter	Near-Term
$m_{reactor}$ (kg)	3000
P_{gen} (MW _e /m ³)	500
B (Tesla)	8
s_t/\mathbf{r} (kJ/kg)	309
\mathbf{r}_c (kg/m ³)	1×10^4
j_c (A/m ²)	1×10^9
U_{regen} (W/m ² ·K)	500
\mathbf{b}_{regen} (kg/m ²)	1.0
\mathbf{e}_{rad}	0.9
\mathbf{b}_{rad} (kg/m ²)	1.0
\mathbf{h}_{thrust}	50 %
\mathbf{a}_{thrust} (kg/kW _e)	0.5





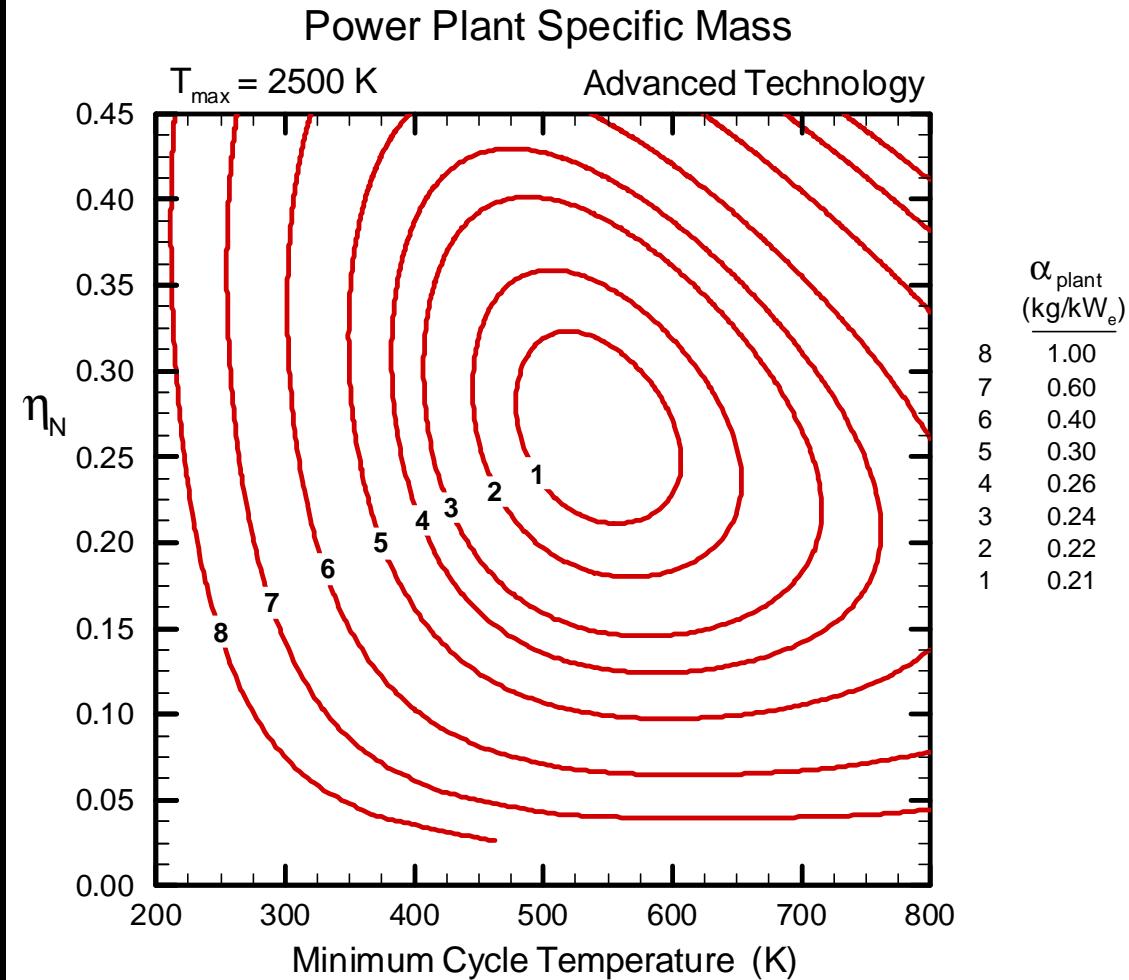
Power Plant Specific Mass: Advanced Technology

Marshall Space Flight Center

Disk MHD Brayton Power Plant

Subsystem Technology Assumptions

Parameter	Advanced
$m_{reactor}$ (kg)	3000
P_{gen} (MW _e /m ³)	500
B (Tesla)	8
s_t/r (kJ/kg)	580
r_c (kg/m ³)	3×10^3
j_c (A/m ²)	1×10^9
U_{regen} (W/m ² .K)	500
b_{regen} (kg/m ²)	1.0
e_{rad}	0.9
b_{rad} (kg/m ²)	0.2
h_{thrust}	60 %
a_{thrust} (kg/kW _e)	0.4

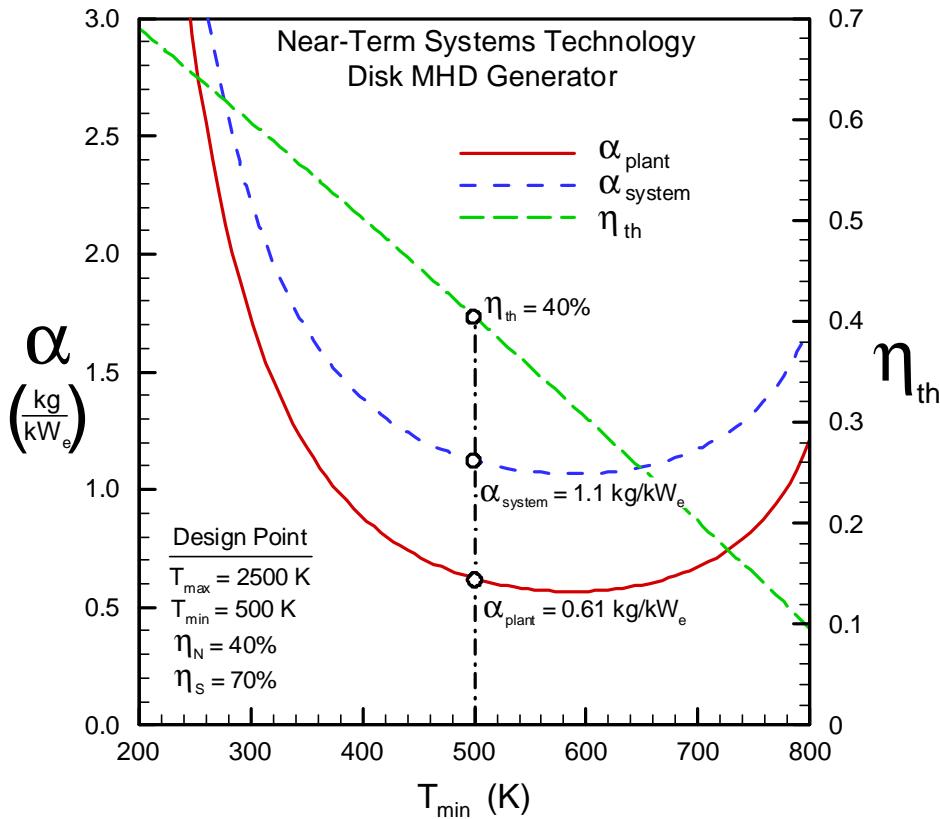




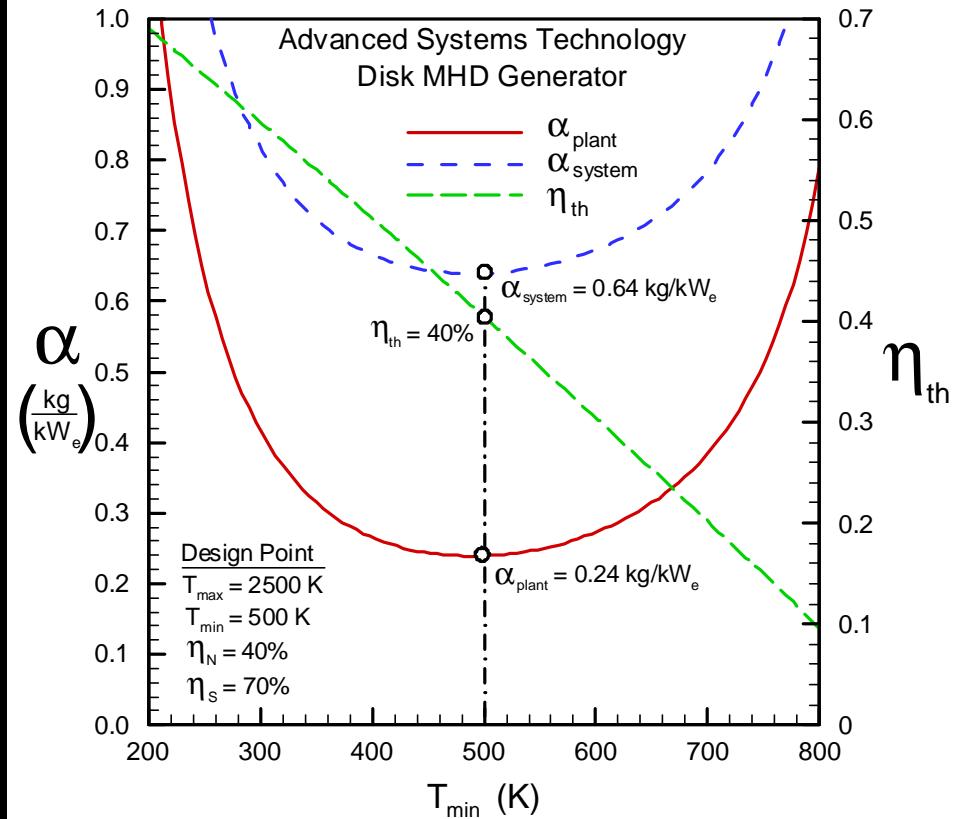
Design Point Specific Mass: $h_N = 40\%$, $h_{s,g} = 70\%$

Marshall Space Flight Center

Near-Term Systems Technology Disk MHD Brayton Power Plant



Advanced Systems Technology Disk MHD Brayton Power Plant





Design Point Thermodynamic States

Marshall Space Flight Center

MHD Brayton Power Plant

Helium Working Fluid

$$T_{\max} = 2500 \text{ K}$$

$$T_{\min} = 500 \text{ K}$$

$$e_{\text{regen}} = 0.9$$

$$h_{s,g} = 0.70$$

$$h_{s,c} = 0.87$$

$$p_g = 8 \quad (h_N = 0.4)$$

Power Balance

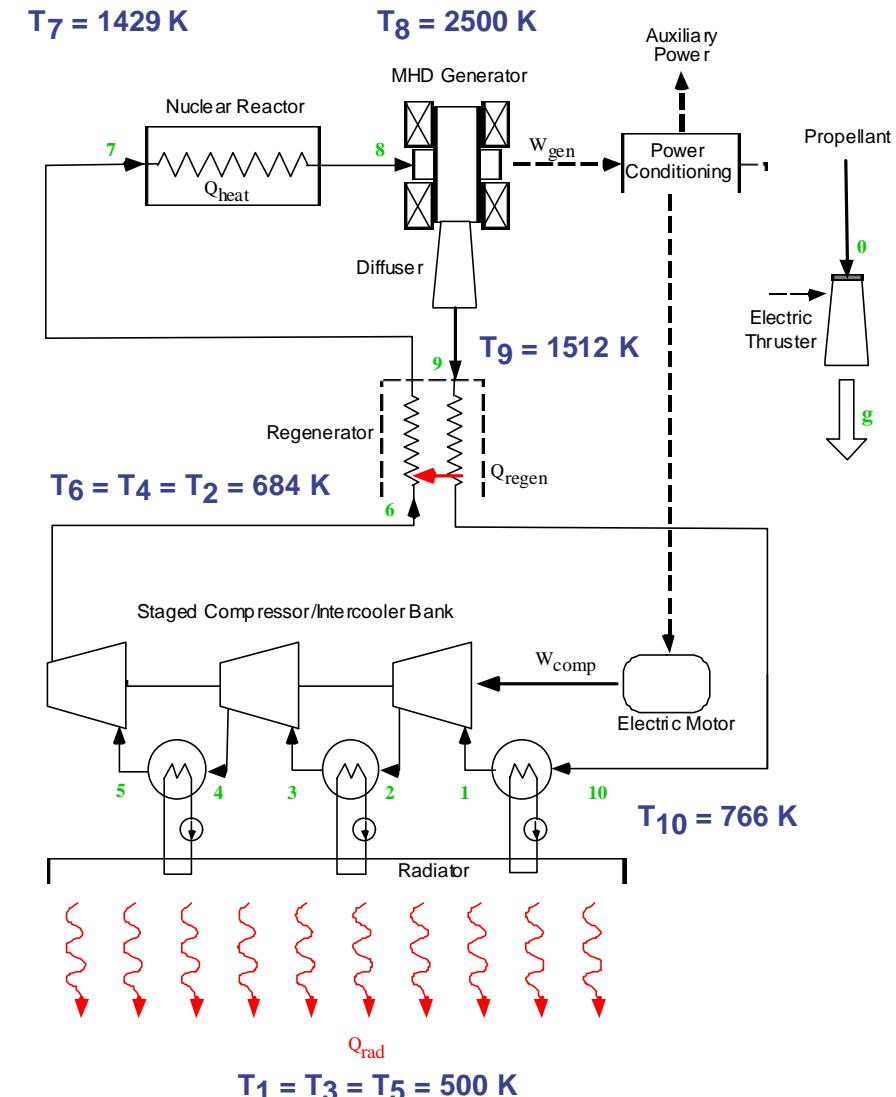
$$h_{\text{th}} = 0.4 \quad (W_{\text{thruster}} = 40 \text{ MW}_e)$$

$$\dot{m} = 18 \text{ kg/sec}$$

$$W_{\text{gen}} = 91 \text{ MW}_e$$

$$W_{\text{comp}} = 51 \text{ MW}_e$$

$$Q_{\text{rad}} = 60 \text{ MW}_{\text{th}}$$



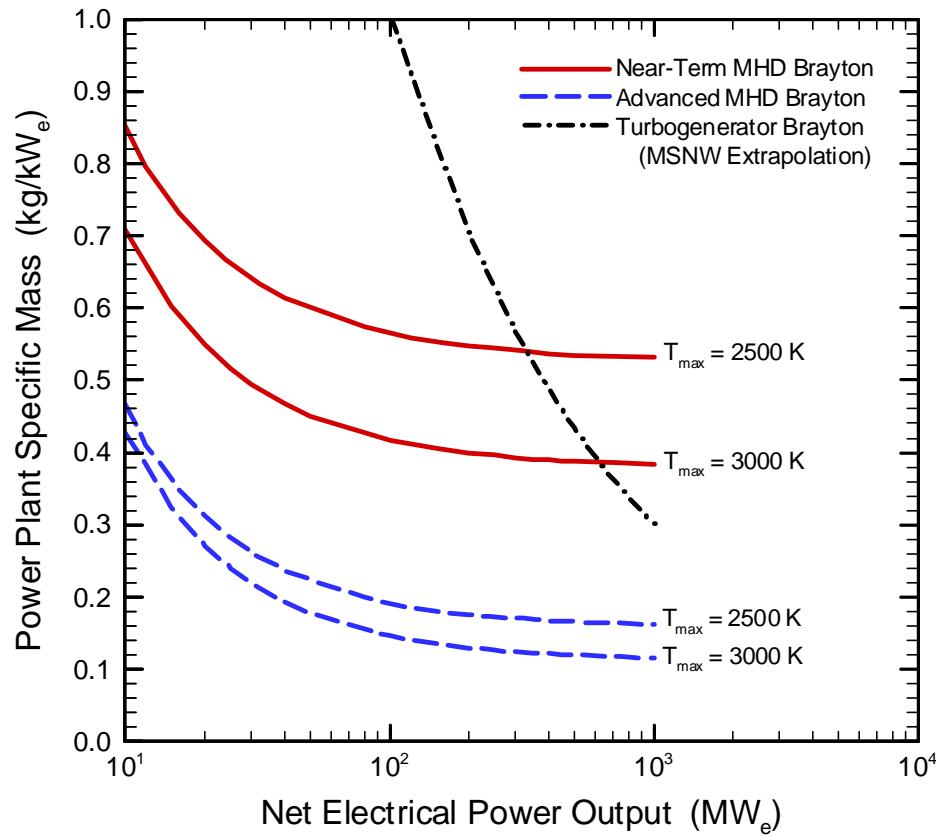


Power Scaling: $T_{\min} = 500 \text{ K}$, $h_N = 40 \%$, $h_{s,g} = 70 \%$

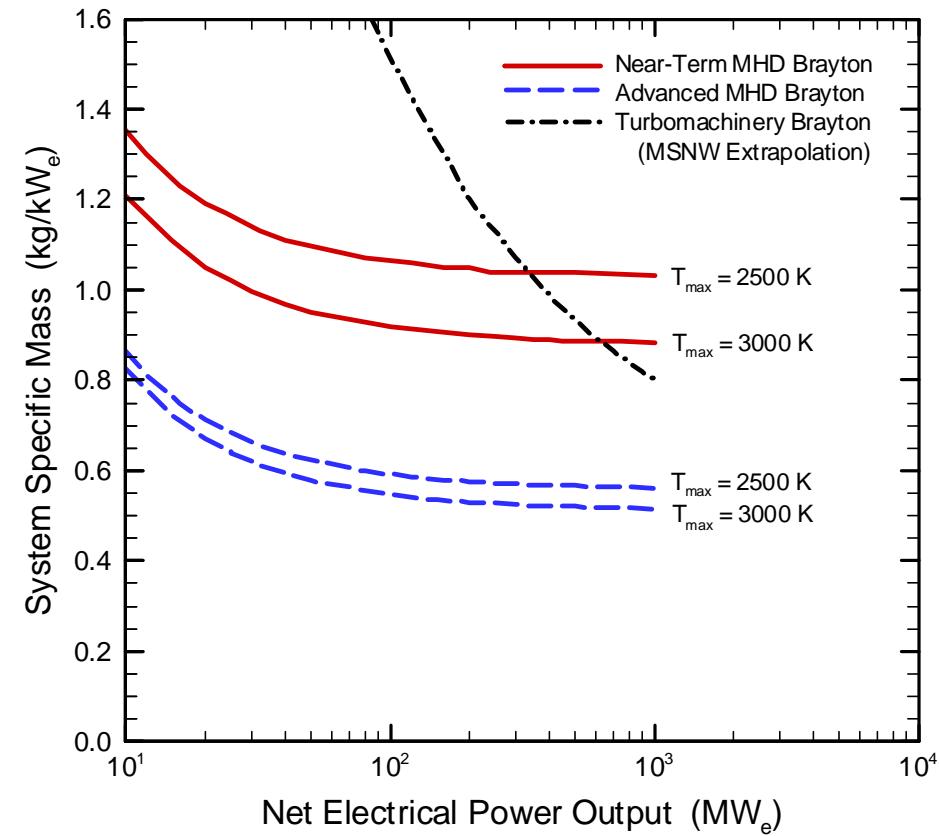
Marshall Space Flight Center

Disk MHD Brayton Power Plant

Power Plant Specific Mass



Propulsion System Specific Mass





MHD Technology Assessment

Marshall Space Flight Center

Projected Efficiency Requirements of MHD Generators ...

Enthalpy Extraction Ratio (h_N): 40 %

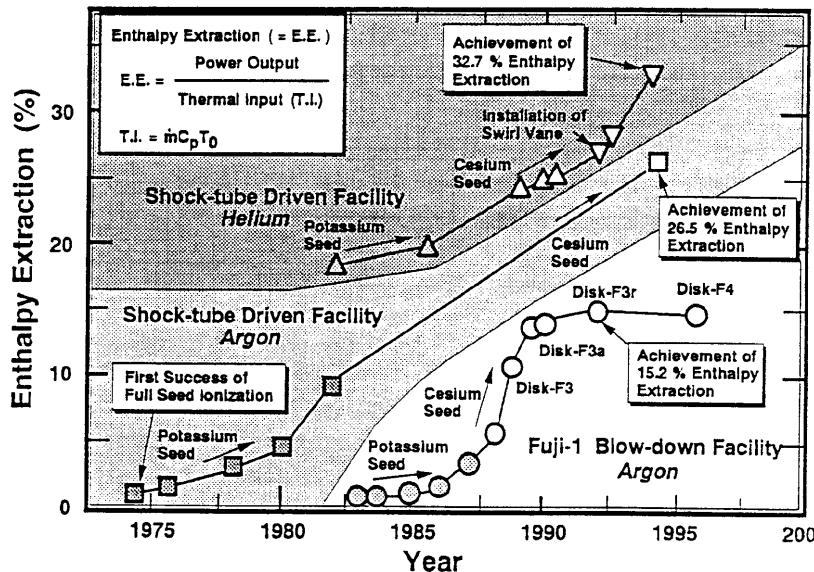
Isentropic Efficiency ($h_{s,g}$): 70 % (65 % minimum)

Demonstrated Efficiency of Nonequilibrium Hall Disk Generators ...

Enthalpy Extraction Ratio (h_N): »30 %

Isentropic Efficiency ($h_{s,g}$): »50 %

Japanese Research Facilities



... High Efficiency MHD Feasible?



Conceptual Design of MHD Generator

Marshall Space Flight Center

Conceptual Design of Cs Seeded He Disk Inui, Ishikawa, and Umoto (1993)

- Specify $Q_{reactor}$, T_0 , p_0 , h_N , r_{in}
- Restrict F-parameter (plasma stability)
 - $4000 \text{ V/m T} < F < 5000 \text{ V/m T}$
- Specify engineering constraints
 - B (high as practically feasible)
 - outlet Mach number range
 - max wall divergence angle
 - max electric field
 - max current density
 - max effective electrode width

Results for 100 MW_{th} Generator:

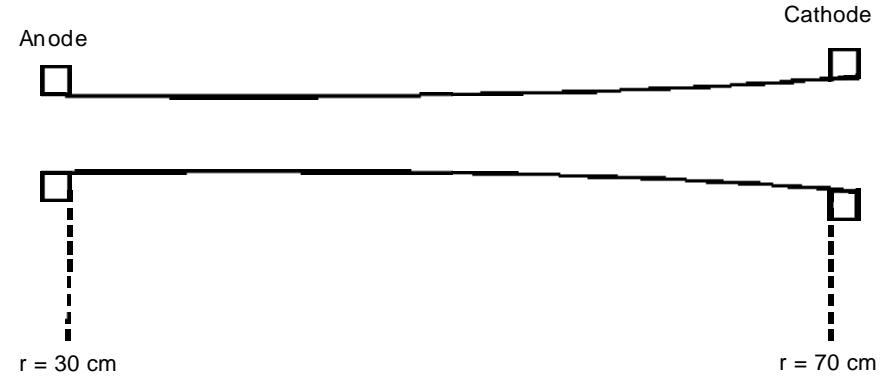
Electron Temperature: $T_e \gg 5000 \text{ K}$

Enthalpy Extraction Ratio: $h_N = 40 \text{ \%}$

Isentropic Efficiency: $h_{s,g} = 87 \text{ \%}$

MHD Disk Design Restrictions

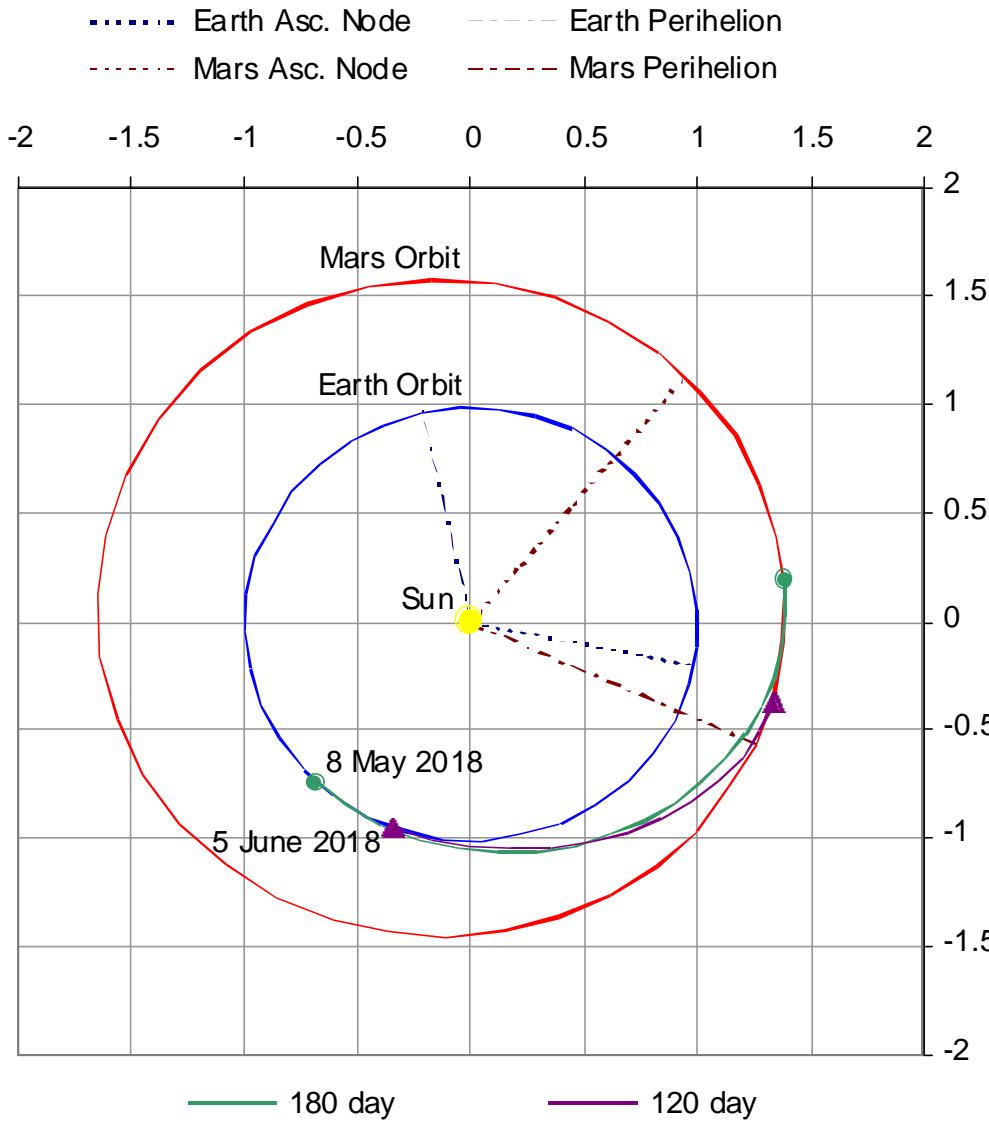
Parameter	Value
$Q_{reactor}$ (MW _{th})	100
T_0 (K)	2200
P_0 (atm)	3
r_{in} (m)	0.3
h_N	40 %
B (Tesla)	8
M_{exit}	1.2
q_{max}	10°
$E_{r,max}$ (kV/m)	35
j_{max} (kA/m ²)	35
Effective Electrode Width (m)	0.025





Benchmark Assessment for Piloted Mars Mission

Marshall Space Flight Center



Mission Parameters:

- **2018 Mars Opportunities**
- **100 MT Baseline Payload**
- **Out-Bound Transit (Only)**
 - spiral out of 1000 km earth orbit
 - thrust/coast in heliocentric space
 - spiral into 500 km mars orbit
- **120, 150, 180 Day Transits**

Optimization Methodology:

- **CHEBY-TOP Code**
- **Minimal Propellant Usage**
 - departure date
 - trajectory
- **Optimal Power (Optional)**

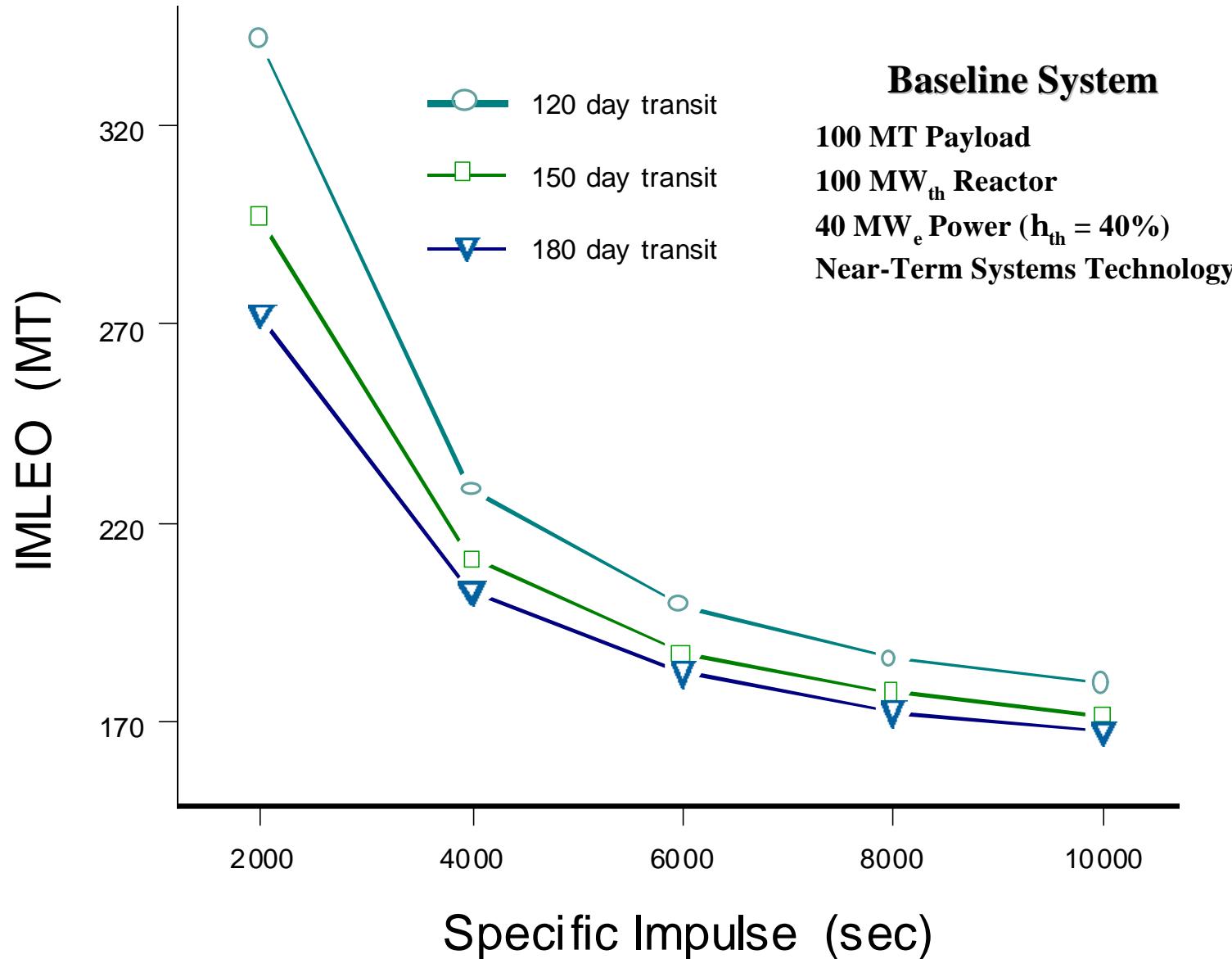
Baseline System Parameters:

- **100 MW_{th} Reactor**
- **40 MW_e Power ($h_{th} = 40\%$)**
- **Near-Term Systems Technology**



Trajectory Optimization for Baseline System

Marshall Space Flight Center

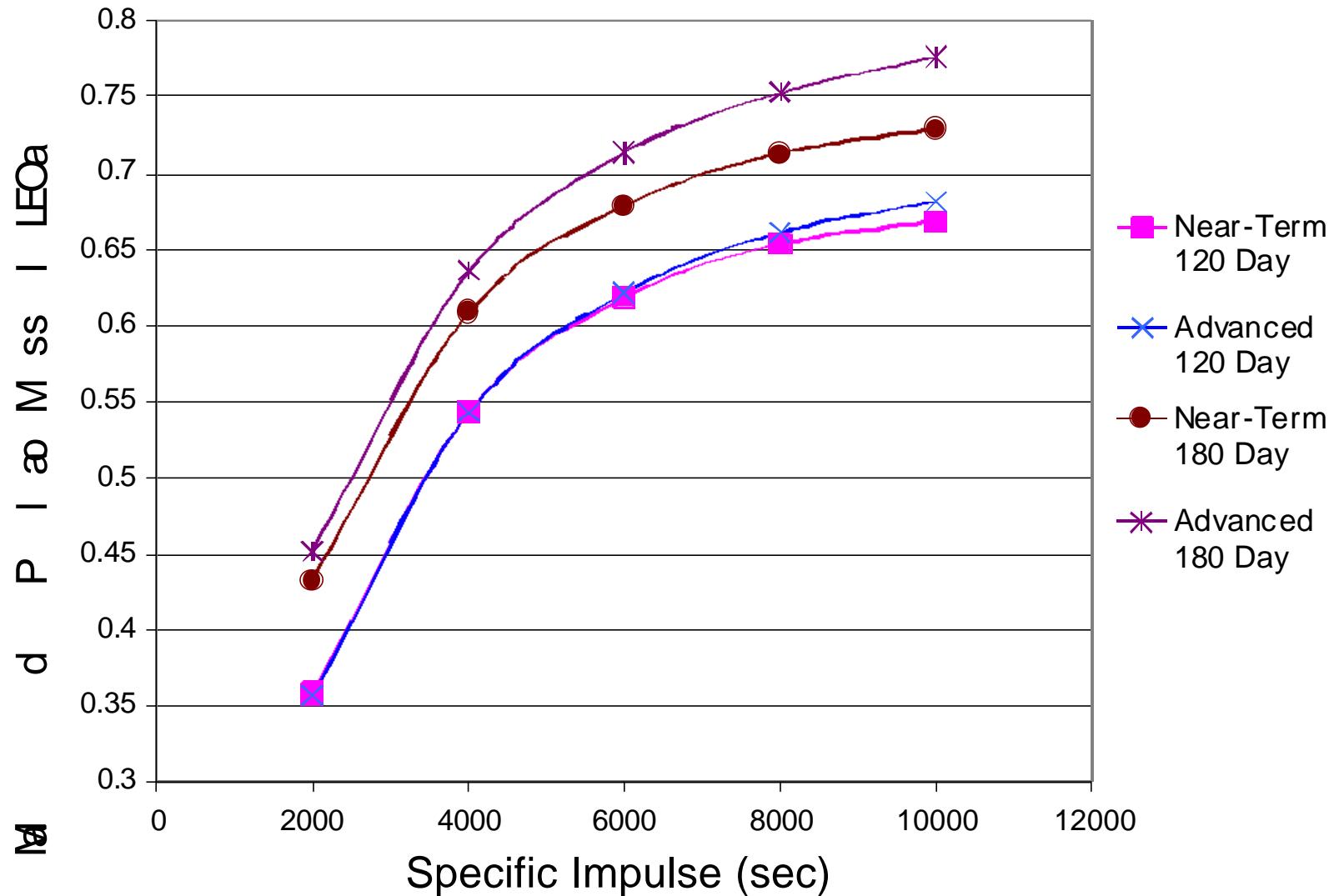




Power Optimization

Marshall Space Flight Center

100 MT Payload





- Nuclear MHD Powered Electric Propulsion Enables Deep Space Exploration
 - adequate energy density
 - potential for very low specific mass
 - scientific & engineering feasibility / clear technology development paths
- System Analysis of Nuclear MHD Brayton Power Plant with MMW EP
 - thermodynamic cycle analysis / specific mass analysis ® trends/sensitivities
 - near-term: $a_{\text{system}} \gg 1 \text{ kg/kW}_e$ / long-term: $a_{\text{system}} < 1 \text{ kg/kW}_e$
- Nonequilibrium MHD Power Generation is a Maturing Technology
 - conceptual designs indicate practical feasibility & adequate efficiencies
 - obtainable efficiencies appear adequate
- Major Technological Hurdles
 - develop efficient MW-class electric thrusters
 - develop long-life high-temperature fissile fuels (to 3000 K)
 - improve nonequilibrium MHD generator efficiencies (h_N ® 40% / $h_{s,g}$ ® 70%)
 - develop lightweight SC magnet & space radiator technologies
 - demonstrate useful system operating times (e.g., severe thermal environments)

... High Near-Term Payoff Potential with Moderate Risk



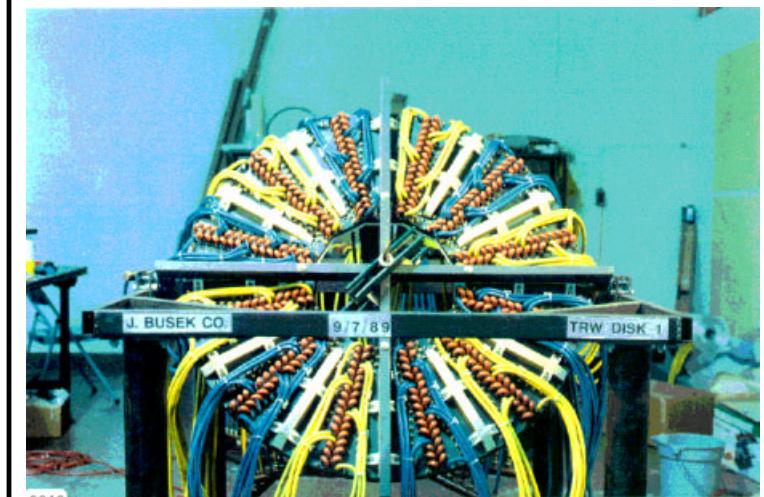
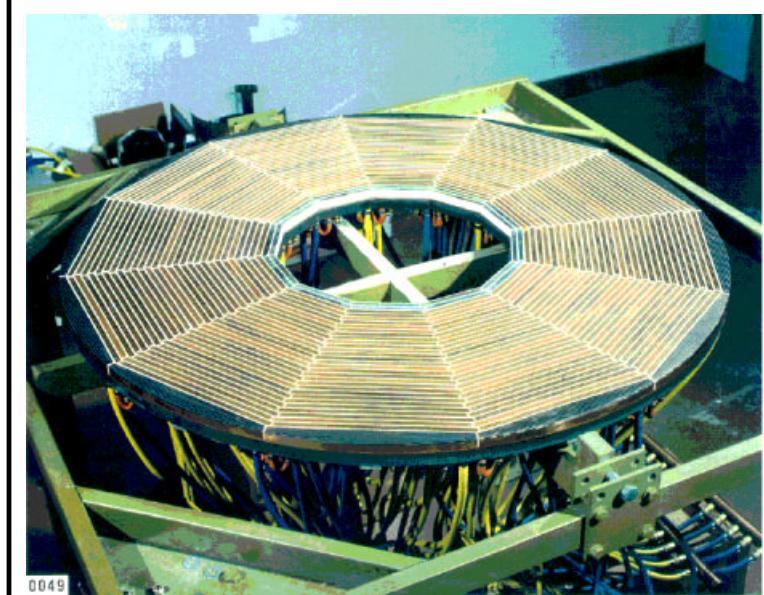
NASA MSFC MHD Disk Generator Unit

Marshall Space Flight Center

MHD Disk Generator Unit

- **10 MW MHD Disk Generator Unit**
 - DOE contract to TRW (SDI Program)
 - fabrication subcontract to Busek Co.
 - technology demo for space power
- Unit built but never tested (placed in storage)
 - demise of SDI program
- Recently acquired from DOE by NASA MSFC
 - MHD propulsion system research facility
 - Electrically powered driver in procurement
 - Nonequilibrium retrofit lofting calculations completed

Inlet Diameter	34 cm
Exit Diameter	94 cm
Height	7 cm
Inlet Swirl Parameter	+1
Exit Swirl Parameter	+0.012
Magnetic Field	4 Tesla



... Questions / Comments

Space Transportation Directorate

